



Determination of Appropriate Infiltration Models in Subsurface and Surface Flow Applications

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USACE Groundwater-Surface Water Interaction Studies

- Coastal Louisiana
- South Florida/Everglades Restoration



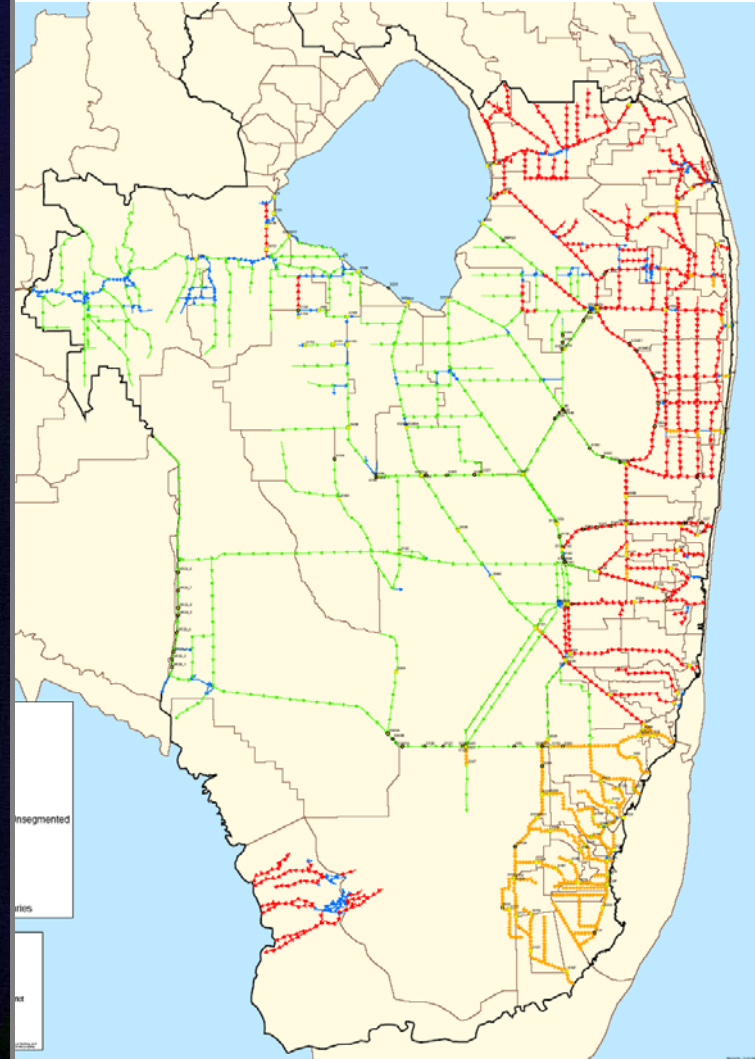
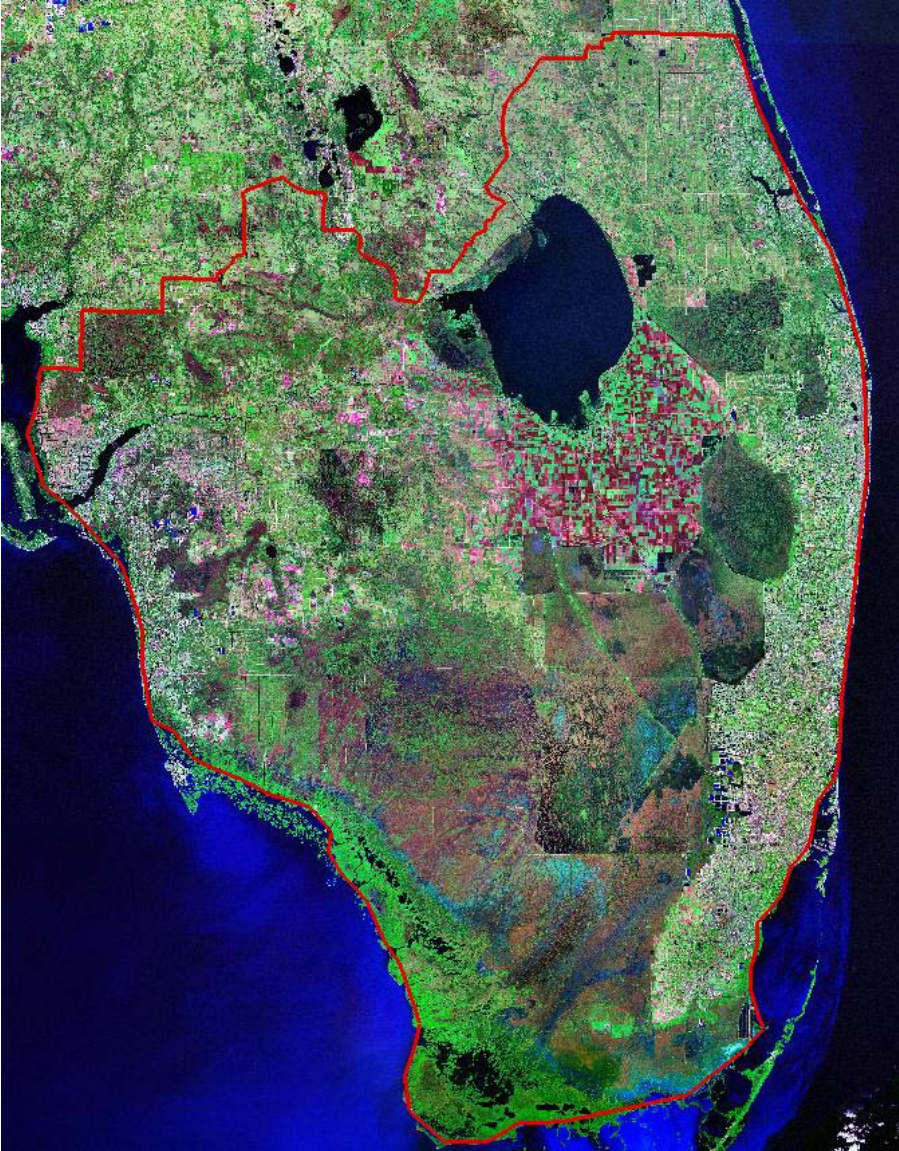


Scale of South Florida Study





South Florida Challenges



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Canals, Agriculture, Population, Preservation

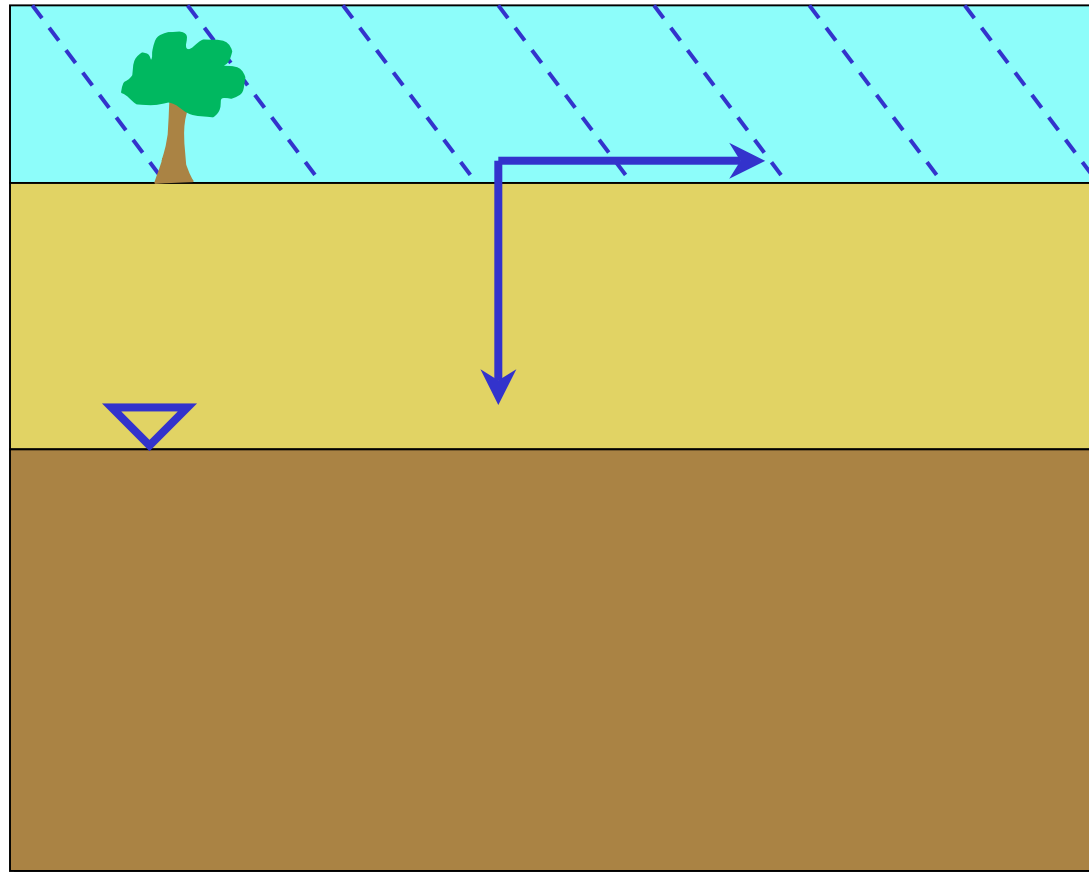


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Large-scale GW-SW Interaction Infiltration Modeling Goal

- Get the fluxes right!





Current USACE Tools for GW-SW Interaction

- GSSHA
- WASH123D
- ADH





Current USACE Tools for GW-SW Interaction

■ GSSHA

- distributed, physically-based Gridded Surface Subsurface Hydrological Aalysis (GSSHA) model (Downer and Ogden, 2003)
- simulates 2D overland flow, 1D channel routing, 2D saturated groundwater flow, canopy retention, microtopography, infiltration and ET using finite-difference and finite-volume methods

■ WASH123D

■ ADH

Downer, CW and FL Ogden. 2002. GSSHA User's Manual, Gridded Surface Subsurface Hydrologic Analysis Version 1.43 for WMS 6.1. ERDC Technical Report, Engineering Research & Development Center, Vicksburg, MS





Current USACE Tools for GW-SW Interaction

- GSSHA
- WASH123D
 - Water flow and contaminant and sediment transport in WaterShed systems (Yeh et al, 2004)
 - First-principle, physics-based finite element watershed model simulating 1D canal, 2D overland and 3D subsurface flow and transport
- ADH

Yeh, G. T., G. Husng, H. P. Cheng, F. Zhang, H. C. Lin, E. Edris, and D. Richards, 2004. *A First-principle, Physics-based Watershed Model: WASH123D. Chapter 9 in Watershed Models (V. P. Singh, ed.), CRC Press LLC, 6000 Broken Sound Parkway, NW, (Suite 300) Boca Raton, FL 33487, USA.*





Current USACE Tools for GW-SW Interaction

- GSSHA
- WASH123D
- ADH
 - ADaptive Hydrology model that simulates flow and transport in coupled surface water - groundwater systems
 - Modular, parallel, adaptive finite element simulation of 2D and 3D dynamic wave surface water and 3D Richards' equation groundwater flow and transport

Schmidt, J. H. 1997. "Chapter 27: 3-D Adaptive Grid Modeling for Groundwater Mechanics," in Next-Generation Environmental Models and Computational Methods, edited by G. Delic and M. F. Wheeler, Society for Industrial and Applied Mathematics, pp. 265-270.





Available Infiltration Methods

- GSSHA
 - Green & Ampt w/ Redistribution
 - Sacramento Soil Moisture Model
 - 1-D Richards' Equation
- WASH123D
 - 3-D Richards' Equation
- ADH
 - 3-D Richards' Equation





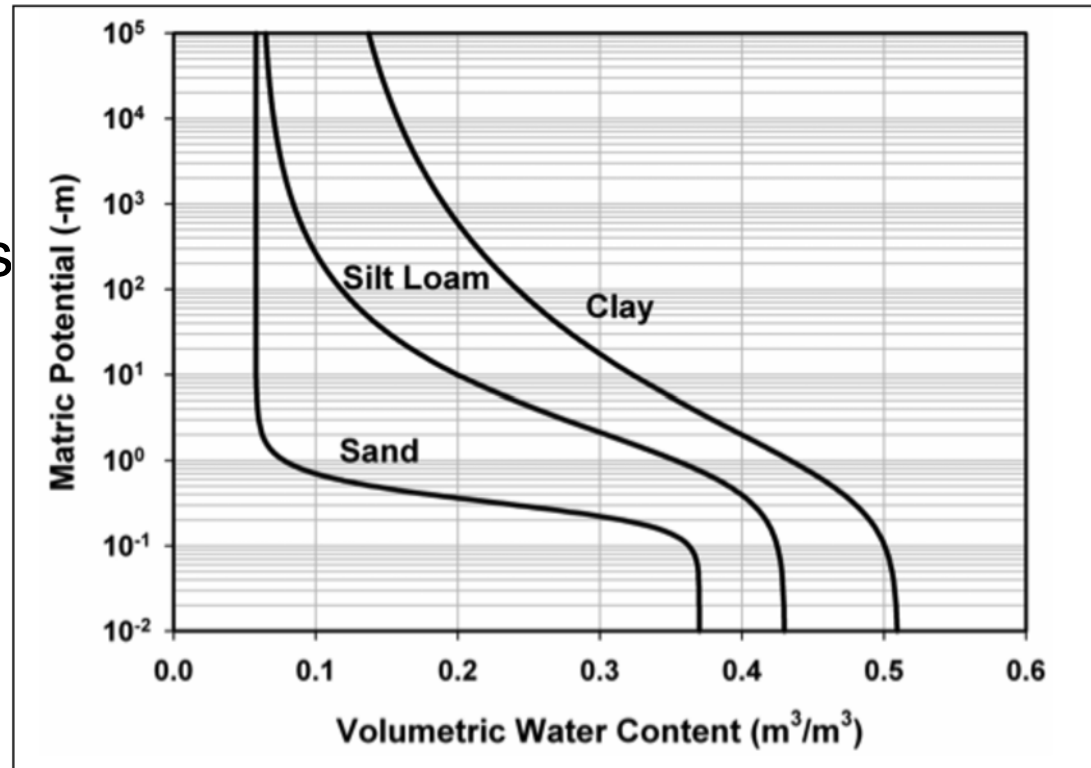
Richards' Equation (1931)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial Z} \left(K(\theta) \left(\frac{\partial \psi}{\partial Z} + 1 \right) \right)$$

The 1D mixed form of the Richards Equation where:

- θ is volumetric soil moisture content (L^3/L^3)
- $K(\theta)$ is hydraulic conductivity as a function of θ (L/T)
- ψ is the soil water matric potential (L)
- Z is depth (L)
- t is time (T)

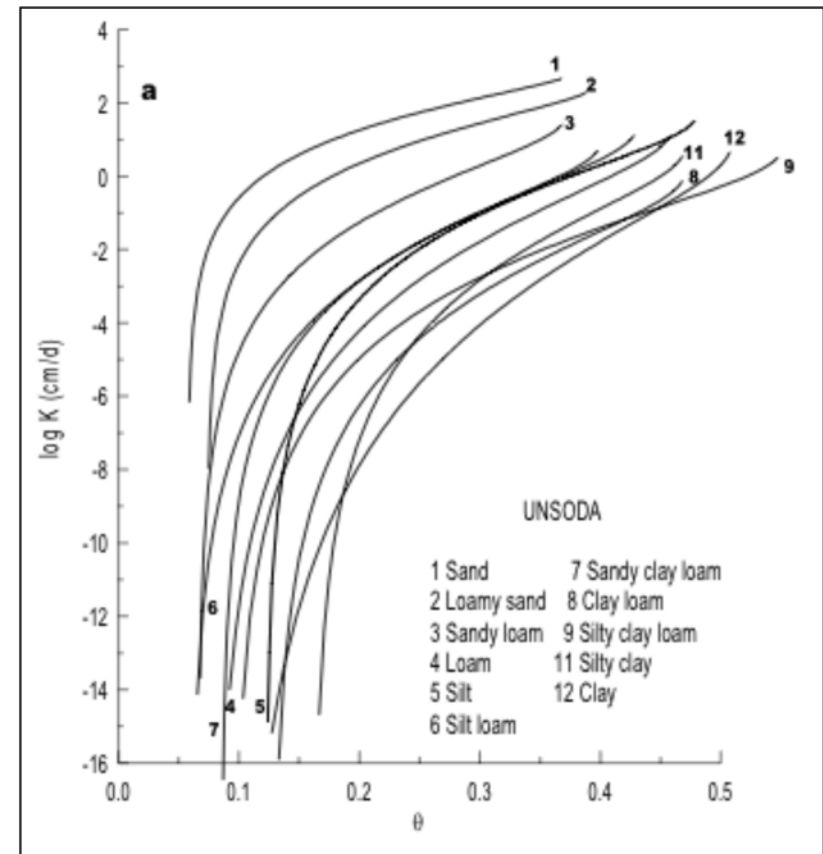
- RE solutions yield θ - ψ or pressure-saturation curves over the entire vadose zone
- Potentially very robust





Vadose Zone Challenges

- RE is highly non-linear due to $K(\theta)$ relationship
- Can commonly vary over 8 orders of magnitude for a single soil sample





Appropriate Vertical Discretization for RE

- Downer & Ogden (2004) addressed the appropriate vertical discretization issue on Hortonian and non-Hortonian watersheds
- Performed spatial (grid) convergence studies using GSSHA with 1D RE to simulate vadose zone fluxes
- Vertical discretization varied from 0.1 to 100 cm (Hortonian) and 0.2 to 50 cm (non-Hortonian) in top 1 m of vadose zone

Downer, CW and FL Ogden. 2004. Appropriate vertical discretization of Richards' equation for two-dimensional watershed-scale modelling. Hydrol. Process. 18:1-22.





Grid Convergence Study

- If a grid convergence study for a non-linear PDE demonstrates model convergence with increased spatial resolution, then solution scheme is both consistent with the PDE and numerically stable
- A grid convergence study can also determine the required resolution to accurately represent a system





Study Results

- Vertical resolution on order of 1 cm was needed near soil surface (but not throughout vadose zone) to properly simulate soil fluxes
- Inadequate resolution can lead to several problems:
 - Large (~2000%!) errors in surface fluxes
 - Erroneous conclusions about the sensitivity of physical parameters in the model
 - Physically unrealistic parameter values
- With proper meteorological inputs and sufficient resolution, RE is able to correct for errors in initial moisture content
- Sufficient resolution at soil surface is critical in proper initiation of infiltration process





Infiltration Approximation Alternatives

- Dozens of models available
 - Physically-based
 - Philip, Green & Ampt, Smith-Parlange...
 - Semi-empirical
 - Horton, Holtan, Singh-Yu, Overton...
 - Empirical
 - Kostiaikov, Huggins-Monke, Collis-George...
- All are limited by simplifying assumptions, many in the case of high and rising water tables
- None are capable of accurately simulating gravity-driven, unstable infiltration

Mishra, S.K., J.V. Tyagi and V.P. Singh, 2003. Comparison of infiltration models. Hydrological Processes. 17:2629-2652.





System-Wide Water Resources Program (SWWRP)

- 7-year U.S. Army Corps of Engineers research and development initiative designed to assemble and integrate the diverse components of water resources management across large scales (systems)
- Assemble tools and methods for watershed, river, reservoir, estuarine, coastal or combined (system-wide) analyses to forecast physical, chemical, and biological response to water resource management activities.





SWWRP: GW-SW Interaction Tools

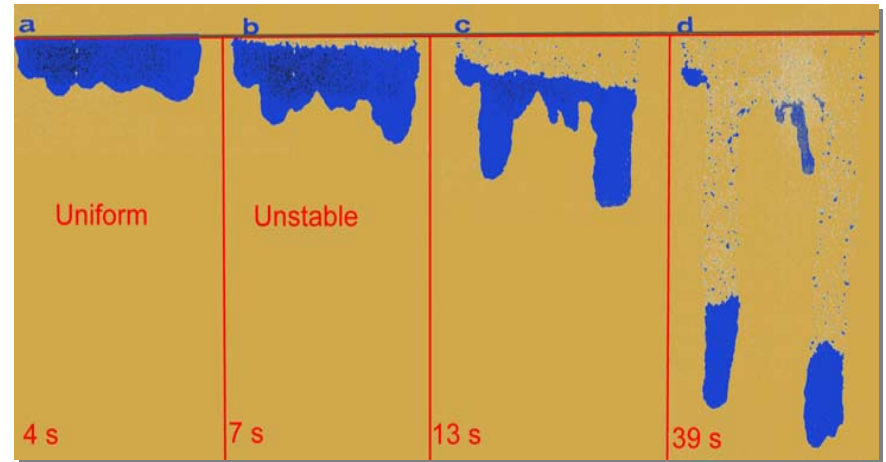
- Development of toolbox of infiltration models for use in GW-SW interaction studies
- Protocol for selection of method based on physical conditions that affect infiltration
 - Soil type, topography, land use, vegetation, initial soil moisture, etc.
 - “License to simplify” or, in other words, we desire a physics-based answer to the two-part question: “when *can* I not use RE and when *should* I not use RE?”





Stable Infiltration Diagnostic

- Stable (capillary-driven) vs. unstable (gravity-driven) infiltration



$$B_o = \frac{(\rho_f - \rho_a)ga^2}{\sigma_{f-a}}$$

Is Bond number (B_o) a suitable diagnostic?





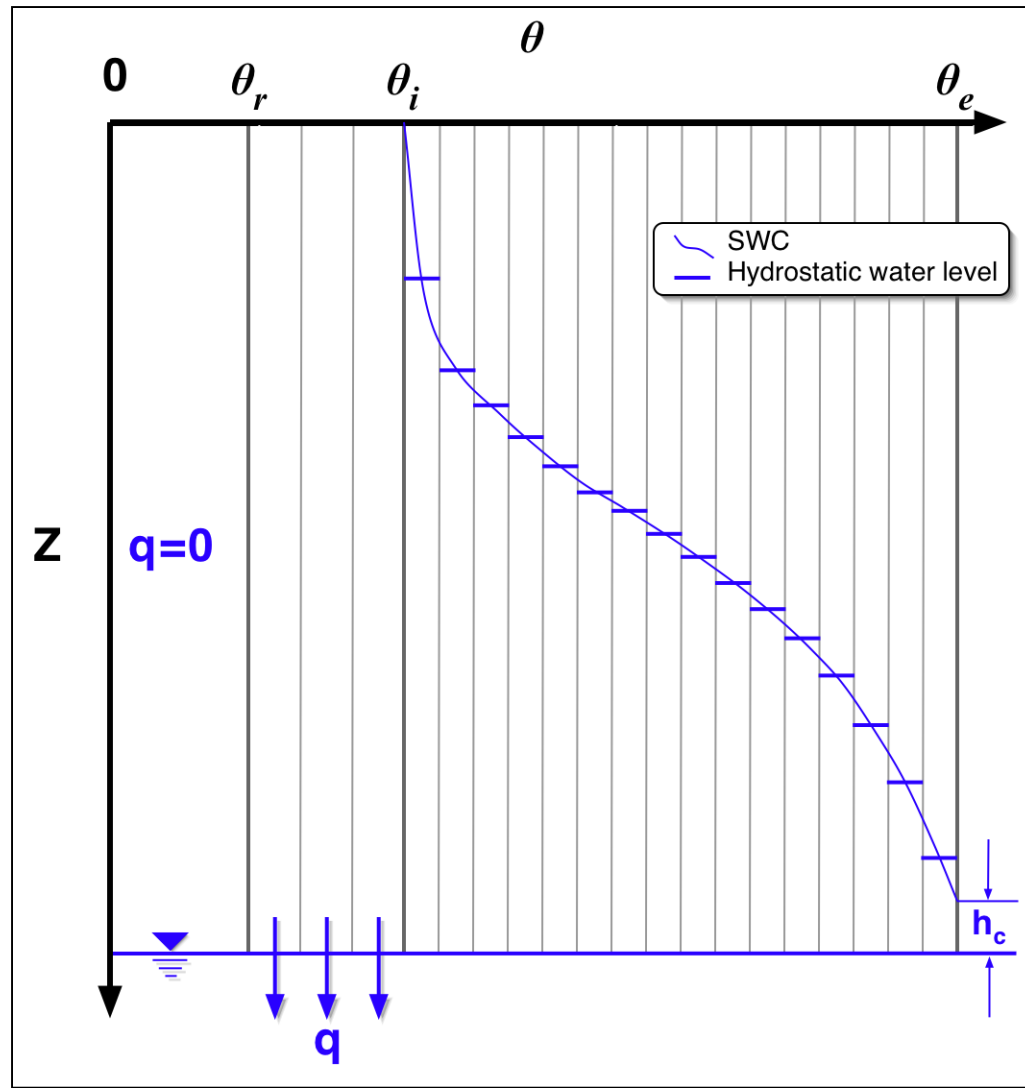
MINC Infiltration Model

- Multiple Interactive Continua models are often used by fractured flow models to simulate the interaction between the disparate flow regimes in the fractures and the surrounding rock matrix
- In our infiltration model, the interactive continua are realized as the soil matrix is discretized into a finite number of “bins” of like-sized pores





MINC Infiltration Model





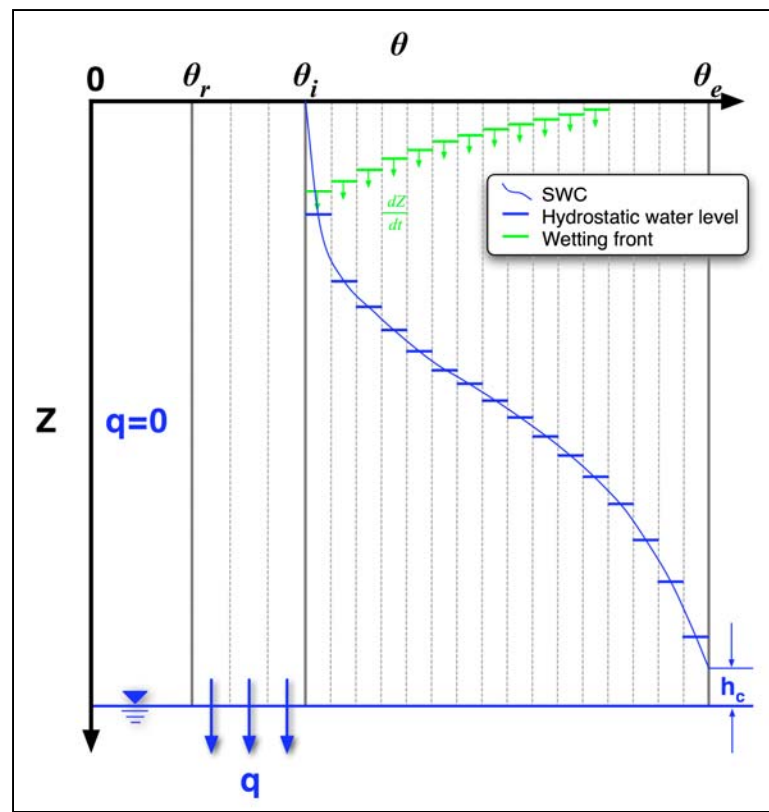
MINC Infiltration Model

- Speed of infiltration in any given bin is calculated from:

$$\frac{dZ}{dt} = \frac{1}{(\theta_o - \theta_i)} \left(\frac{K_s G(\theta_i, \theta_o)}{Z} + K(\theta_o) \right)$$

- Capillary drive term, G is calculated from:

$$G(\theta_i, \theta) = H_c \left(\frac{\Theta^{3+1/\lambda} - \Theta_i^{3+1/\lambda}}{1 - \Theta_i^{3+1/\lambda}} \right)$$



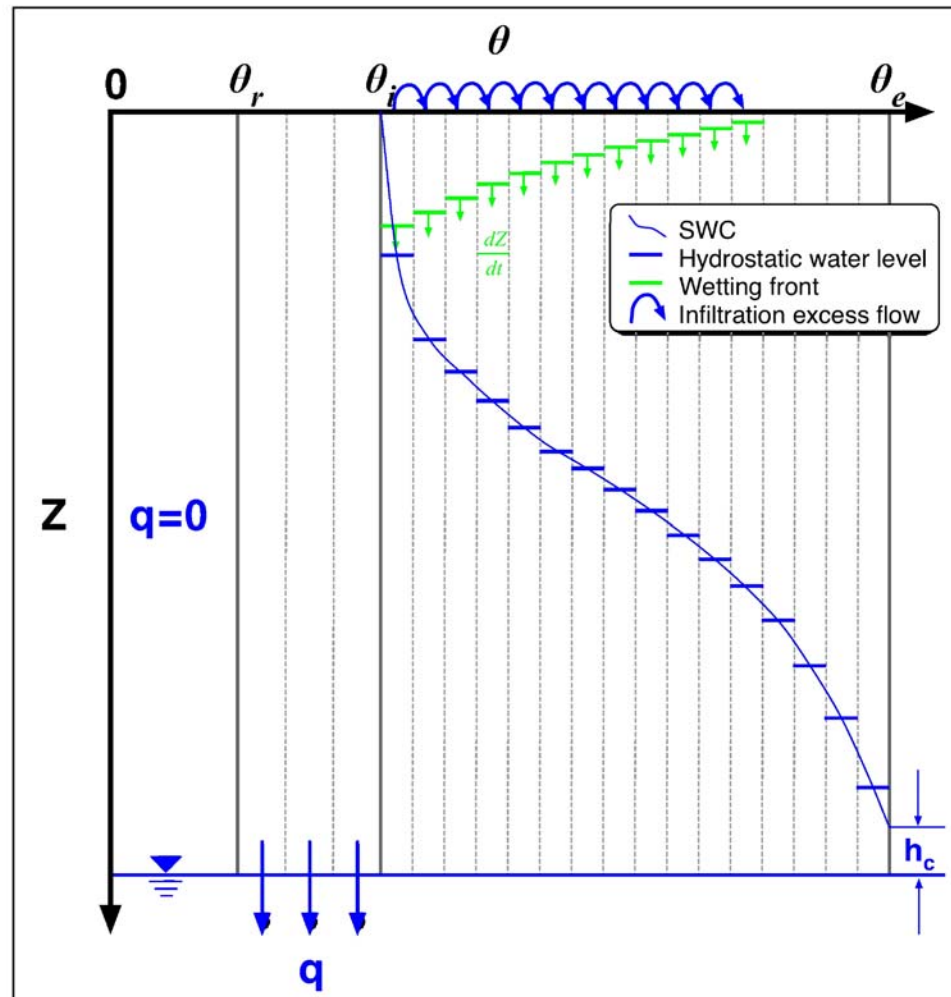
Ogden, FL and B Saghaian. 1997. Green and Ampt Infiltration with Redistribution. *J Irrigation and Drainage Engineering*. **123**:386-393.





MINC Infiltration Model

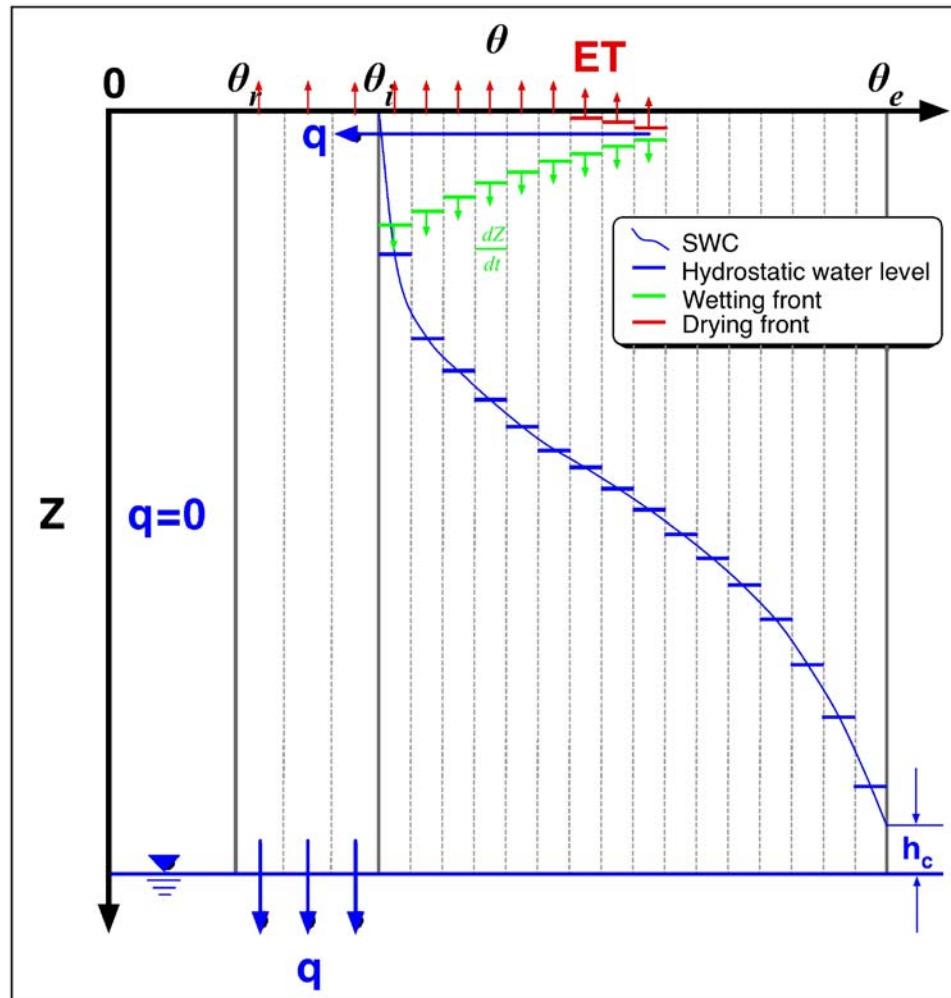
- During precipitation periods





MINC Infiltration Model

- During non-precipitation periods





MINC Infiltration Model Advantages

- Pressure-saturation curve is defined at any time by location of fronts throughout entire vadose zone, alleviating the need for fine near-surface discretization
- After the initial time step, front movement is determined via computationally inexpensive calculations
- Approach is not limited by depth to water table conditions





Concluding Remarks

- USACE is building a toolbox of GW-SW interaction tools for large scale project needs
- Also developing a protocol for physically appropriate selection of an infiltration model
- MINC infiltration model appears to offer distinct advantages over other approximation methods while also dramatically reducing the computational cost of RE
- Stay tuned for interesting results!

